AD-A193 892   COMBUSTION STUDIES OF ACOUSTICALLY SUSPENDED LIQUID   1/1
              DROPLETS(U) ARMY BALLISTIC RESEARCH LAB ABERDEEN
   PROVING GROUND MD   MAR 88 BRL-CR-594

UNCLASSIFIED   F/G 20/1   NL
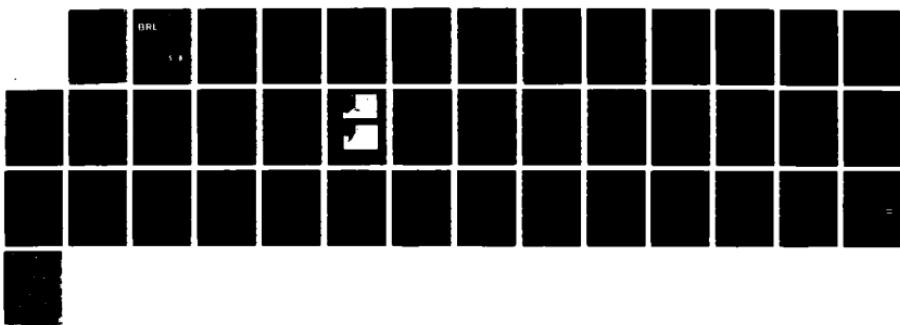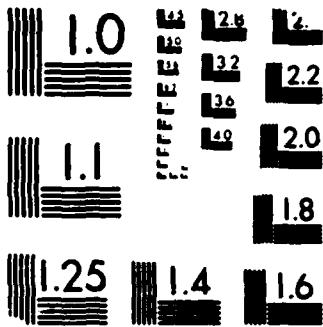
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

④

BRL

1938 – Serving the Army for Fifty Years – 1988

AD–A193 892

COMBUSTION STUDIES OF ACOUSTICALLY SUSPENDED LIQUID DROPLETS

DEPT. OF MECHANICAL ENGINEERING
CORVALLIS, OR 97331

DTIC
ELECTE
APR 2 5 1988
S
E
D

MARCH 1988

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

88 4 25 100

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a REPORT SECURITY CLASSIFICATION		1b RESTRICTIVE MARKINGS AD-A198 892
Unclassified		
2a SECURITY CLASSIFICATION AUTHORITY		3 DISTRIBUTION / AVAILABILITY OF REPORT
2b DECLASSIFICATION / DOWNGRADING SCHEDULE		Approved for Public Release; Distribution Unlimited.
4 PERFORMING ORGANIZATION REPORT NUMBER(S)		5 MONITORING ORGANIZATION REPORT NUMBER(S)
Delivery Order 0430		BRL-CR-594

6a NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
Oregon State University		US Army Research Office
6c ADDRESS (City, State, and ZIP Code)		7b. ADDRESS (City, State, and ZIP Code)
Dept. of Mechanical Engineering Corvallis, OR 97331		P.O. Box 12211 Research Triangle Park, NC 27709-2211

8a NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
Ballistic Research Laboratory	SLCBR-IB	

8c ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
Aberdeen Proving Ground, MD 21005-5066	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
(Dr. John A. Vanderhoff)	61101A	A91A		

11 TITLE (Include Security Classification)

COMBUSTION STUDIES OF ACOUSTICALLY SUSPENDED LIQUID DROPLETS

12 PERSONAL AUTHOR(S)

Richard B. Peterson

13a TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Report	FROM 22 May TO 30 Sep		44

16 SUPPLEMENTARY NOTATION

Task was performed under a Scientific Services Agreement issued by Battelle, Research Triangle Park Office, 200 Park Drive, P.O. Box 12297, Research Triangle Park, NC 27709

17 COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Ultrasonic Resonator
21	02		Acoustic Levitation
9	01		

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A piezoelectrically driven ultrasonic resonator was developed and tested in this study. The device was used to levitate liquid fuel droplets for evaporation measurements and ignition studies. The final report describes the resonator and its operating characteristics, gives a brief review of the literature, and presents the results of various ignition tests. No successful minimum perturbation ignition method was discovered among the several explored. It is the author's opinion that the acoustic levitation technique may hold some promise for conducting non-combustion related droplet measurements, for example evaporation tests, but without further development of the technique combustion experiments will be difficult to be accomplished. Minimum developmental needs will be for a high temperature, high pressure chamber and a feedback positioning controller. However, even with such additional features there is some doubt whether stable levitation of a burning droplet can occur.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION	
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Dr. John A. Vanderhoff	301-278-7069	SLCBR-IB-I

DD Form 1473, JUN 86   Previous editions are obsolete.   SECURITY CLASSIFICATION OF THIS PAGE

TABLE OF CONTENTS

3

LIST OF FIGURES

SUMMARY

Piezoelectrically driven ultrasonic resonators were found to be simple in design, construction, and testing. Over a dozen resonator configurations were made and tested for their operating characteristics. Two proved to be especially reliable at levitating droplets and were subsequently employed in vaporization and ignition studies on liquid fuels such as ethanol, n-heptane, iso-octane, and decane. These tests were performed at resonant frequencies of approximately 20 kHz and 50 kHz, the former value being a fundamental resonator frequency and the latter value being a first harmonic. Droplet stability in suspension was not as good as desired for accurate determinations of droplet diameters. However, the stability was more than adequate to test various ignition techniques which included use of a) hot wires, b) spark discharges, c) open flames, d) excimer laser produced air breakdown, and e) CO_2 laser heating. All attempts proved unsuccessful. The reason for this is not known at this time but the effect of the acoustic pressure field on ignition is a key area of concern. Vaporization tests conducted on the droplets demonstrated that the suspending force in the acoustic field is equivalent to approximately a 12 cm/s flow across the droplet. The magnitude of this velocity, although small, could have detrimental effects on the droplet ignition . mechanisms.

1 INTRODUCTION

Much combustion research consists of characterizing the properties of sprays. Due to their complexity, many fundamental aspects important in characterizing spray combustion are obscure. One example of this involves the study of liquid fuel and liquid propellant droplet combustion. Progress in this area has been accomplished not by studies involving spray combustion, but by investigating the burning of isolated single droplets under various conditions. Many techniques have been developed for such studies involving either freely falling droplets or fiber suspended ones. One technique not previously employed in combustion work is droplet levitation. The work reported on here involves an investigation of the acoustic levitation technique and its possible use in studies of liquid fuel and propellant combustion.

Aerodynamic, acoustic, and electrostatic principles have been exploited in the past to design levitation devices where a single droplet could be suspended almost free of motion.[1-3] For our purpose of suspending a liquid fuel or propellant droplet, aerodynamic and electrostatic techniques have been eliminated for the following reasons. With aerodynamic techniques, it is extremely difficult to maintain a gas flow of sufficient stability to keep small droplets stationary. Furthermore, adapting this technique to a high pressure environment adds much more complexity to the system. Electrostatic devices would be expensive, bulky, and not easily adaptable to the high pressure environment necessary to conduct liquid propellant studies. In addition, it is doubtful whether a burning droplet will retain its charge and hence position in the electrostatic field. An acoustic levitation device, on the other hand, has several attractive features; it is relatively inexpensive, it can be made compact and easily incorporated into high pressure vessels, and it has the capability of suspending small droplets motionless.

The approach taken here is the development of a basic piezoelectric driven resonator designed for useful power output in the frequency range between 20 and 60 kHz. Design constraints include compact construction while maintaining a sufficiently strong acoustic pressure field to levitate droplets. For this purpose, a stable frequency source and power amplifier are required to drive the piezoelectric elements of the resonator. The device is used to suspend droplets of various fuels while tests are performed on the levitated specimen. These tests include evaporation measurements and ignition studies. The objectives of this investigation are:

a) Survey the literature for the various designs of piezoelectrically driven ultrasonic resonators.

b) Construct a compact levitator which is driven by piezoelectric ceramic elements. Overall dimensions not to exceed 2.5 inches in diameter and 7.5 inches in length.

c) Acoustically suspend liquid drops in the diameter range of 0.3 to 1.0 millimeters.

d) Find optimum operating parameters of the acoustic levitator for making drops motionless.

e) Find a minimal perturbation igniter technique for ignition of acoustically suspended combustible liquid drops.

f) Ignite an acoustically levitated combustible droplet and monitor the stability as combustion takes place.

g) Render an evaluation on the practicality of using acoustic levitation to study combustion phenomena of individual liquid drops.

This report describes the work accomplished toward fulfilling these objectives during the contract period of 22 May to 30 September 1987. During the course of this work, various resonator designs and clamping techniques were considered and several resonators were built and tested. An evaluation of the most reliable design has been provided in this work.

2 REVIEW

Ultrasonic resonators have been employed for a variety of applications.[4-6] For example, one design based on a piezoelectric driven resonator was used for atomization of fuel oil.[4] The vibration of the resonator end caused a liquid sheet of fuel covering it to break off in the form of droplets with an average diameter of 25 micrometers. A vibrational frequency of 60 kHz was used in this study. Atomized fuel collected at the planes of sound pressure minima when a reflector was used to set up a standing wave pattern in air. Fuel delivery to the end of the resonator was accomplished through a center tube so that liquid could be supplied to the resonator at a vibrational nodal point. Tests on the device demonstrated little wear or fatigue developing after 4×10^{12} cycles at a maximum resonator end stress of 11,000 psi. No clogging was observed with the fuel oil used in the study.

This investigation was note worthy because of the various resonator clamping designs studied. It was shown that clamping techniques were of great importance for obtaining proper acoustic coupling between the piezoelectric drivers and the resonator bulk material. Horn designs were also studied to increase the resonator end displacement amplitude. A stepped horn design proved useful for increasing the acoustic intensity by a factor of 6 to 10 times.

In another study, a high power piezoelectric transducer was designed and tested that generated 10 kW of power at an efficiency of 97.5%.[5] The resonator included a catanary horn

design specially developed for the high power application.
Testing of the system involved attaching two similar devices
together as a motor-generator combination and recording input and
output power. At lower power levels, it was recommended that a
stepped horn be used to obtain high amplification factors.
However, the stepped horn resulted in lower overall efficiency.
The catanary type proved most efficient. The entire assembly
weighed 22 lbs. and produced a 0.004 inch peak-to-peak
vibrational amplitude at the end of the horn. Mild steel was
used in the construction of the resonator.

An in depth study of the stability of acoustically suspended
liquid droplets demonstrated that droplets move towards planes of
minimum sound pressure at resonance.[6] In a resonator/reflector
configuration, the first two sound pressure minima where shown to
be the best. In the untuned state where the reflector distance
was not set to the optimal spacing, the pressure maxima were well
below the tuned pressure minima. Using a hot wire to map out the
velocity in the acoustic field, the peak velocity positions were
identified. Further experiments showed that a radial distribu-
tion of sound pressure existed and provided a means of
stabilizing droplets in the radial direction. This was
demonstrated by showing stable levitation with the resonator
rotated through 90 degrees.

Other studies using a spherical resonator geometry have been
conducted.[7] The stability of droplets was reported to be
influenced by the ratio of viscous drag to radiation pressure.
When this ratio was between 0.25 and 0.75, the onset of
instability occurred. Experiments demonstrated that droplets
below 0.5 mm in diameter were ejected for the pressure well, thus
falling out of the acoustic field produced by the resonator and
reflector.

Center bolt resonators have been designed and constructed
for studies in space borne laboratories as well as in ground
based facilities.[8] Designs incorporating stepped horns connected

12

to circular vibrating plates for coupling the ultrasonic
vibrations to the environment have shown reliable operation for
positioning specimens in laboratory furnaces and high pressure
vessels. Applications of the levitation equipment included
studies of surface waves on freely suspended liquids, variations
of the surface tension with temperature, and optical diffraction
properties of transparent substances. The criteria for efficient
coupling between the resonator and the acoustic medium is given
where it was shown that the resonator end diameter should be
larger than the wavelength of the sound frequency.

3 RESONATOR DESIGN

The resonator design employed in this work uses the
principle of the piezoelectric effect. A ceramic disk having
this property expands and contracts as an AC voltage differential
is applied across it. In a typical design, two disks are
sandwiched between two metal cylinders. The disks expand and
contract in opposite directions simultaneously. When an AC
signal is applied to the device whose frequency is f, a resonant
wave is set up in the metal cylinders if the overall resonator
length is $\lambda/2$ where $\lambda = c/f$. Here c is the speed of sound in the
metal and λ is the wavelength. The result of the resonant
condition is high amplitude displacement of the two ends of the
device causing sound energy to be transmitted into the
surrounding environment. If a flat reflector is place an
integral number of wavelengths (now in air) from the end of the
resonator, an acoustic standing wave pattern can be set.

The basic resonator design employed in this study is shown
in Fig. 1. Two piezoelectric ceramic disks, with the same
polarity faces together, are sandwiched between two matched
aluminum cylinders. A center hole exists in each of the disks so
that a bolt can be used to clamp the assembly together. A
conductive plate is placed between the two disks to provide an
electrode for driving the piezoelectric elements. The

13

EXPLODED VIEW OF RESONATOR

CENTER ELECTRODE

PIEZOELECTRIC DRIVER

ALUMINUM CYLINDER

PIEZOELECTRIC DRIVER

ALUMINUM CYLINDER

CENTER BOLT

FIGURE 1

14
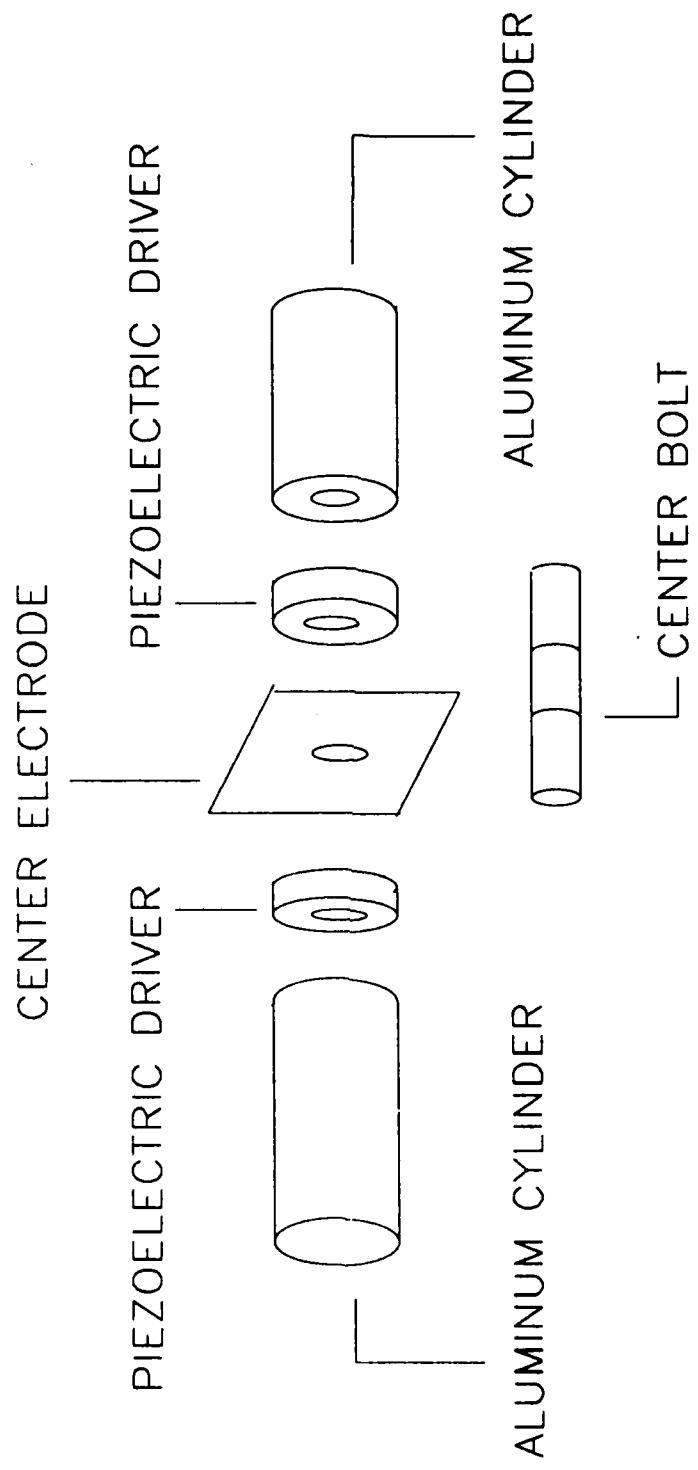
non-threaded section of the bolt is sheathed in insulating
plastic to prevent the center electrode from shorting out to
ground (the cylinders are held at ground potential).

The goal was to produce a resonator that supported fuel
droplets at a resonant frequency between 20 and 60 kHz. The
resonator developed to achieve this goal had a diameter of 1.06
inches. The aluminum (6061-T6) cylinders on each side of the
0.080 inch thick ceramic drivers were 1.825 inches long. A plate
0.060 inches thick was the center electrode for the design. A
center bolt had a length of 1.50 inches, a diameter of 3/8 of an
inch and was made out of 304 stainless steel. The threads on the
bolt were 3/8 inch NC. A resonant fundamental frequency of
slightly below 20 kHz was measured and a first and second
harmonic near 50 kHz and between 90 and 100 kHz, respectively,
were found. Figure 2 shows the experimentally determined
resonant frequencies. A second device having the same length as
above and a diameter of 1.465 inches was also constructed and
proved to be resonant at approximately the same frequencies
(fundamental at 22 kHz). Clamping pressure on the piezoelectric
disks had a significant effect on the resonator efficiency, and
hence sound intensity level. Figure 3 shows the relationship
between the pressure applied to the ceramic disks and the
relative increase in detected sound level. The top graph is for
ceramic disks 0.080 inches thick while the bottom is for disks
0.125 inches thick. As indicated by the graph, the sound level
increased to a point at all three resonant frequencies tested
when the clamping pressure increased.

Two different types of resonators were tested. The center
bolt type described above was used in all experiments reported on
here. Another design, employing flange clamping, was also built
and tested. The flange resonator was never successful at
supporting droplets and since the center bolt resonator was
simple and effective, it was exclusively used in all levitation
experiments. Horns were also studied with various designs being

FIGURE 2

16

FIGURE 3

17
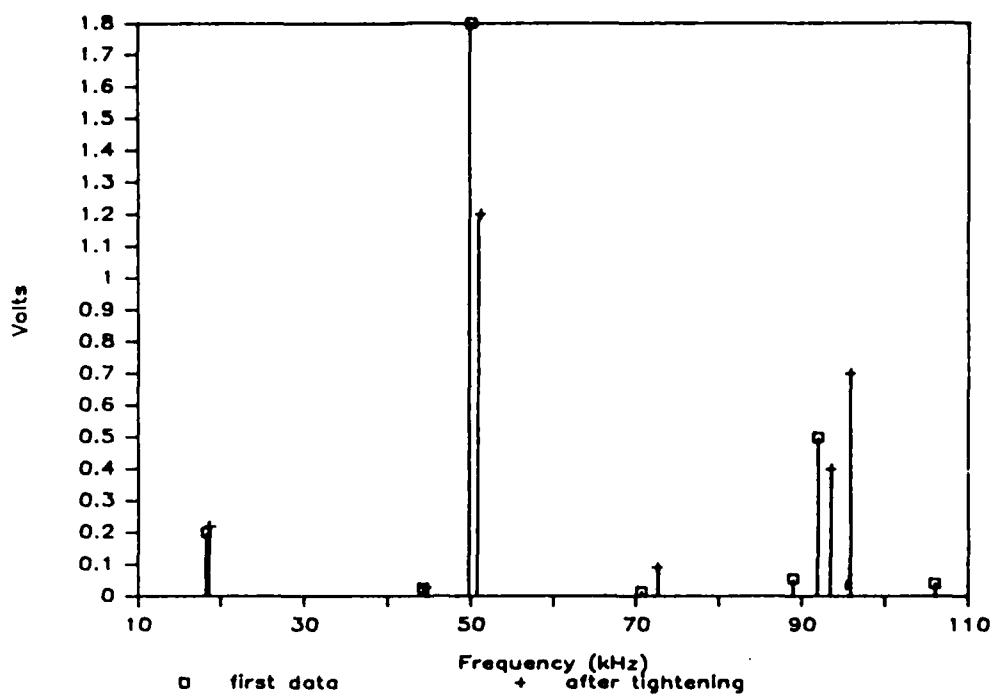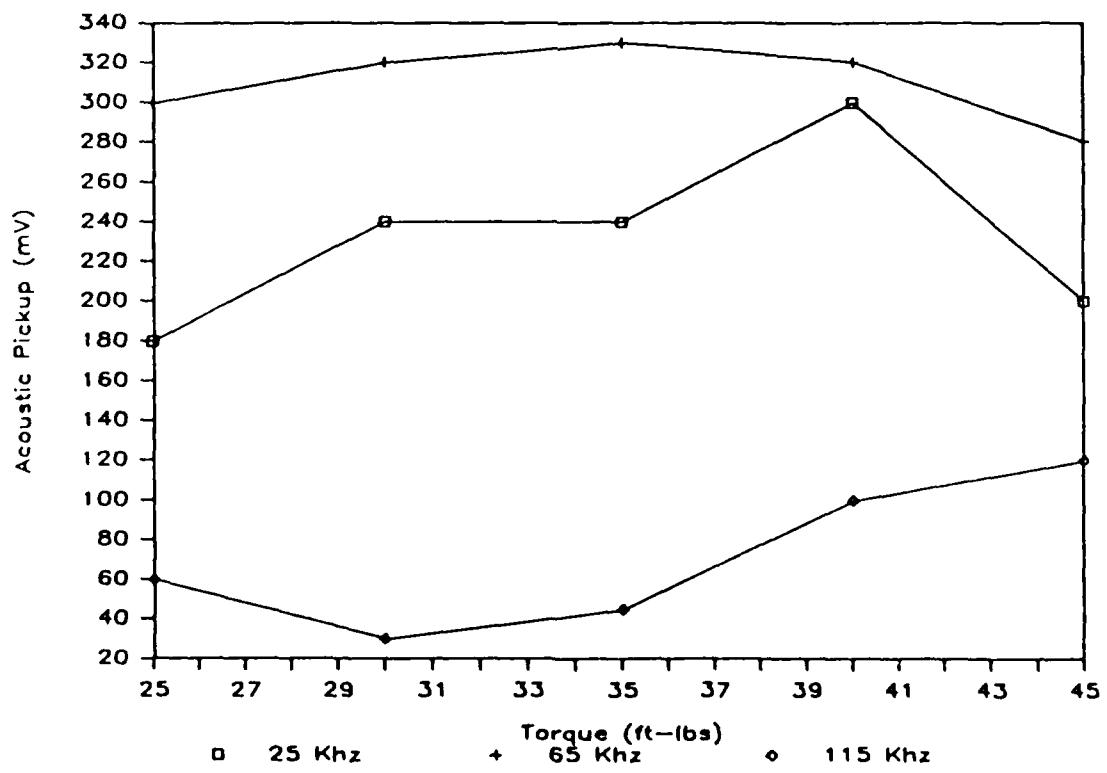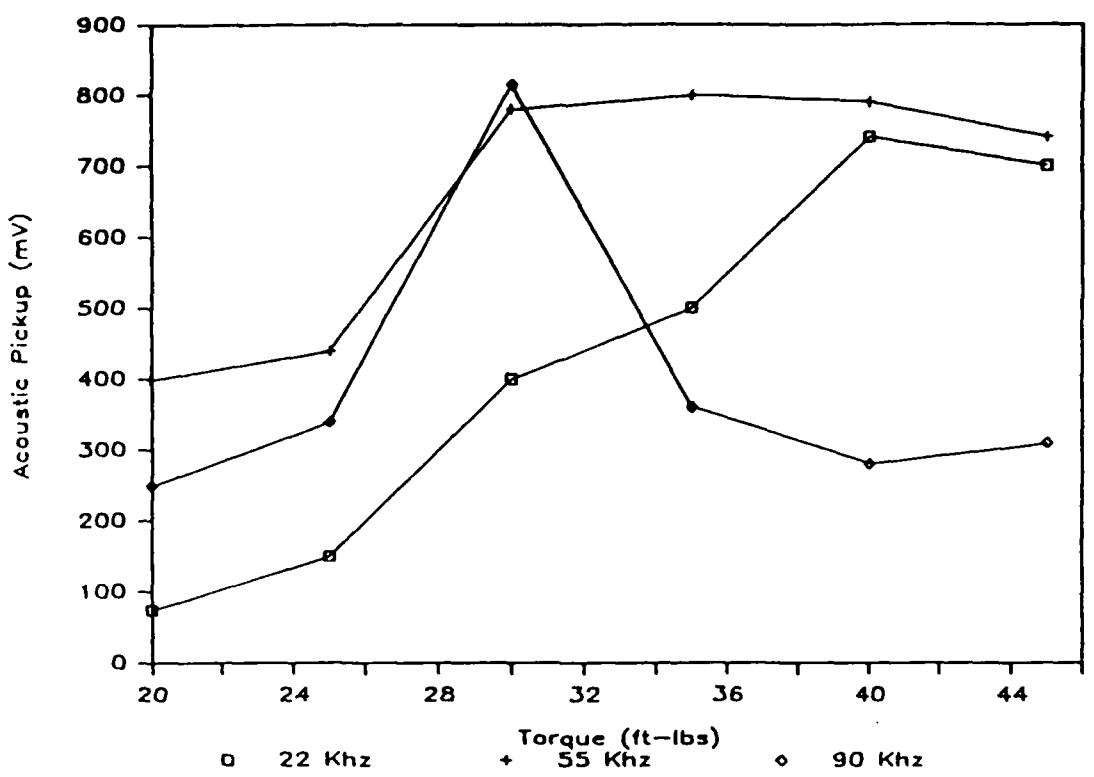
constructed. None appeared to be useful for amplifying the acoustic sound pressure levels, and so they were not pursued further in this study.

The experimental apparatus used to conduct the frequency, sound level, and levitation measurements is shown in Fig. 4. A sine wave generator produced the required signal which was first routed to a counter/timer to obtain an accurate reading of the output frequency, and then to a 10 Watt amplifier for boosting the voltage and power levels of the signal supplied to the resonator. An oscilloscope was used to monitor both the voltage supplied to the resonator and the acoustic signal detected by another ceramic disk which doubled as an effective flat plate reflector. The resonator was mounted in a translator that provided accurate adjustment of the distance between the resonator and the reflector.

4 RESULTS

Droplets were supported at both 20 and 60 kHz with the 1.06 inch liameter resonator. The 1.465 inch diameter resonator only supported drops at a resonant frequency of 22 kHz but proved useful in stability tests and was employed in all evaporation tests with liquid fuels. This resonator closely approach the condition of rendering motionless the suspended droplets hence diameter measurements for evaporation tests were easier to   · perform with this device. Typical driving signals were between 25 and 75 volts peak-to-peak.

Size, stability, and how the droplets were placed on the sound planes were important considerations in this study. Theoretically, the largest droplet diameter that could be levitated in air at 60 kHz, based on the consideration that a droplet cannot cross two sound pressure minima, is 0.4 cm. Experimentally, the largest droplet suspended was ellipsoidal in shape having a mean diameter of 0.2 cm, roughly one half the   · theoretical limit. Attempts to suspend larger droplets produced
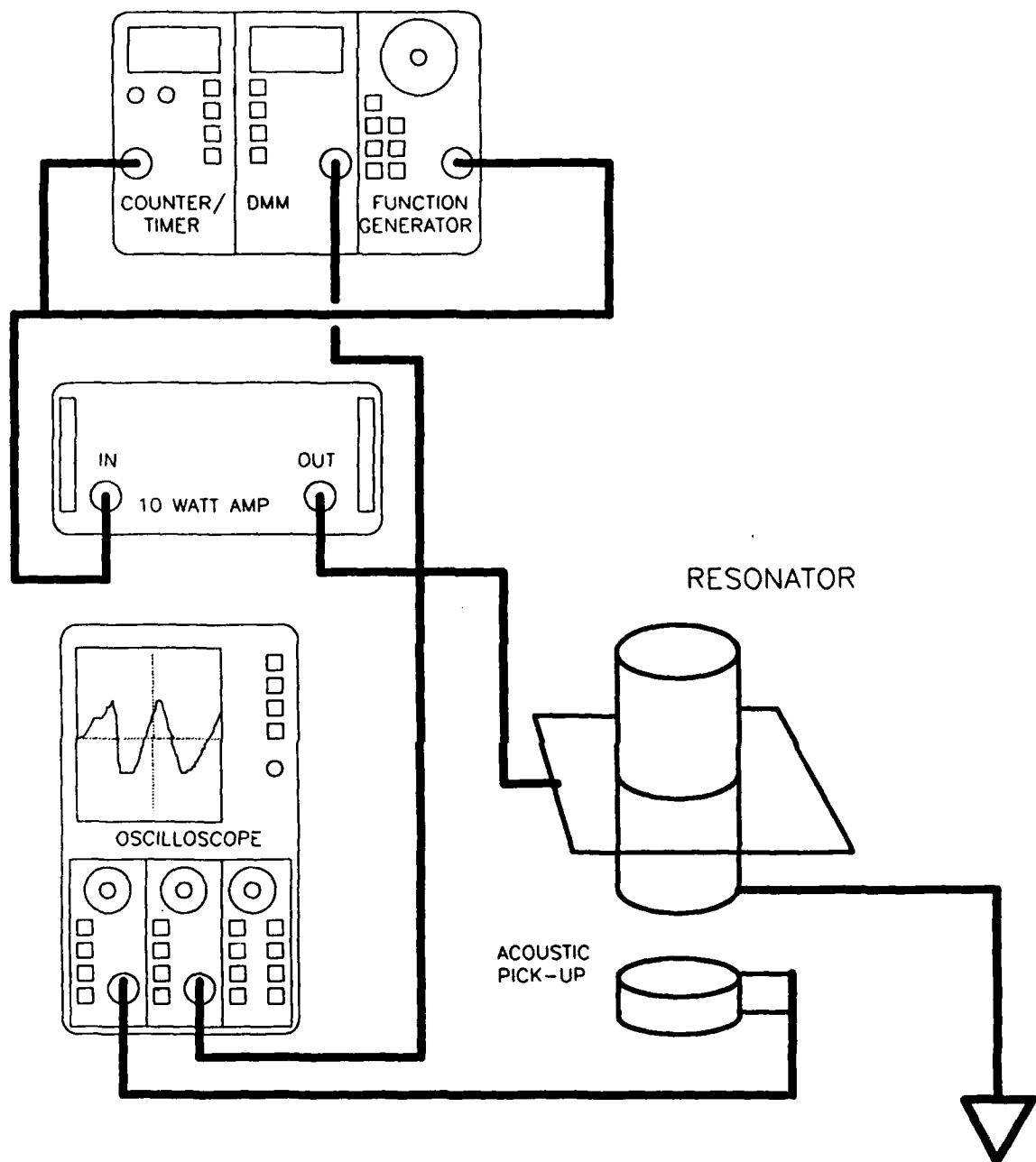
FIGURE 4

a disk shaped specimen as seen in Fig. 5 (top). This disk was 0.1 cm thick and 0.5 cm in diameter. As these disks evaporated, they became spherical and smaller. The smaller spherical droplets tended to oscillate about a fixed point in the acoustic field. The amplitude of oscillation was approximately 0.005 inches. Different fuels oscillated at different rates. For example, methanol vibrated so rapidly that no accurate diameter measurements could be obtained. A droplet was deposited within the acoustic field with a hypodermic syringe and needle. It was important to have a very small tip in order to minimized the surface tension effects keeping the droplet attached to the needle. In some cases, a metal needle was used. In other cases, it proved useful to outfit the syringe with a glass tube that had been drawn down to a fine capillary (100 micrometers in diameter). It was observed that high sound intensity levels permitted easy droplet depositing within the resonant field.

5 VAPORIZATION TESTS

The vaporization tests were performed with the apparatus described above. To observe the size of droplets as a function of time, a binocular microscope was employed having a reticle with a resolution of 0.001 inches. Data from a series of measurements on various liquid fuels can be found in Appendix A. Note that in these measurements the drops oscillated about their equilibrium positions, thus rendering measurements of their diameters difficult. Five runs were averaged together to minimize the errors associated with these measurements.

Theoretical considerations of droplet evaporation in a quiescent environment leads to a linear plot of the droplet diameter squared as a function of time. The linear plot is characterized by a slope of $-\lambda$ calculated by,[9]

$$\lambda = \frac{4 \, Nu \, \rho_g \alpha_g}{\rho_l} \ln(B + 1)$$

20
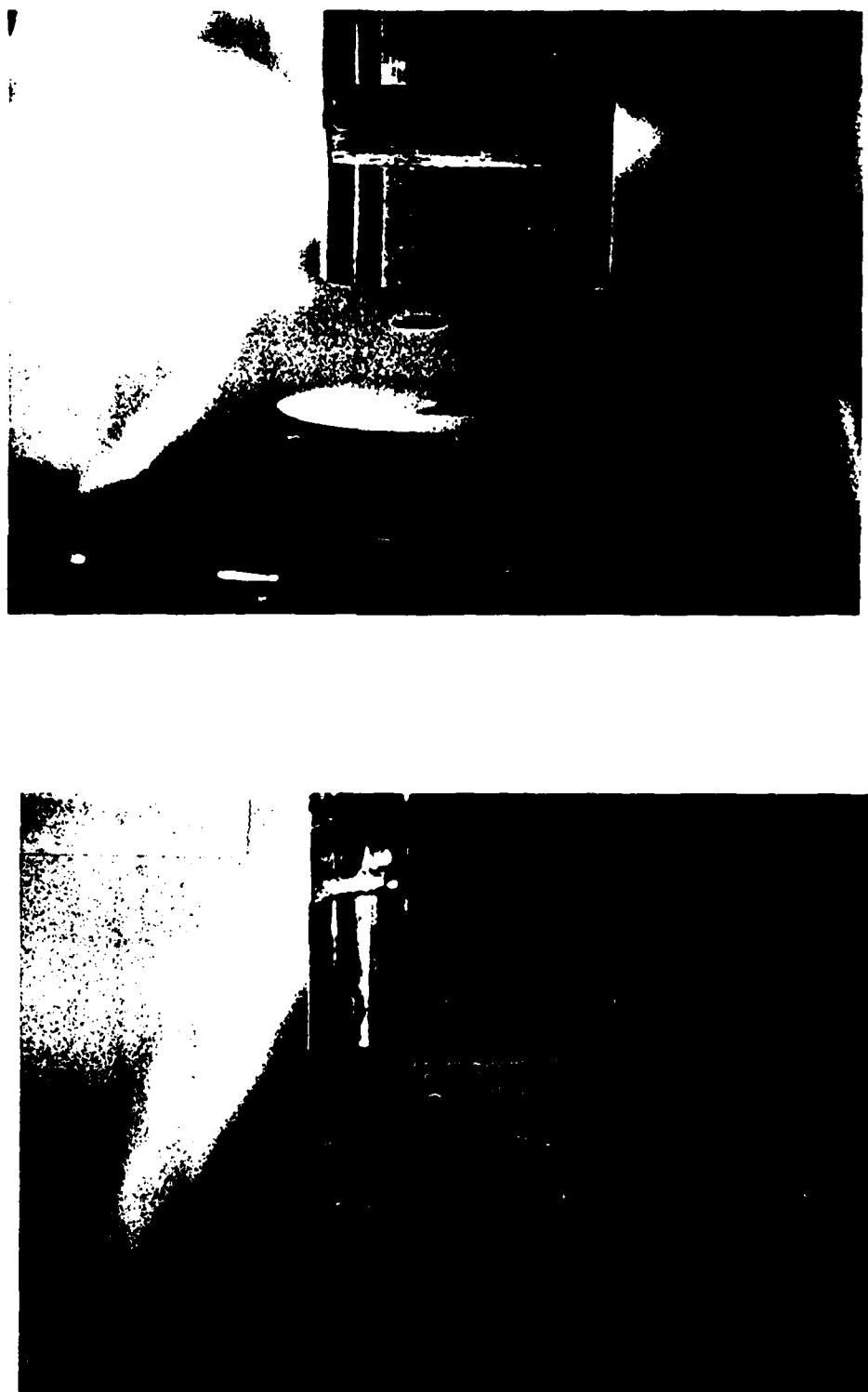
FIGURE 5

B is a nondimensional constant relating diffusion and convection. The Nusselt number is represented by Nu and the density is ρ. α is the thermal diffusivity. Subscripts g and l refer to the gas and liquid phases, respectively. The thermal diffusivity and density can be found in the CRC handbook. When there is no flow by the droplet the Nusselt number is equal to two. For cases of nonzero flow rate where the flow velocity is u, the droplet diameter is d, the kinematic viscosity is ν, and the thermal diffusivity is α, the Nusselt number equals:

$$Nu = 2 + 0.6\left(\frac{ud}{\nu_g}\right)^{\frac{1}{2}}\left(\frac{\nu_g}{\alpha_g}\right)^{\frac{1}{3}}$$

Figure 6 (bottom) shows the results of evaporation tests on ethanol, n-heptane, and iso-octane. The dashed line shows the theoretical results when a flow of 12 cm/s is assumed to pass across a droplet having an initial diameter of 0.03 inches. These comparisons show that a flow is developed by the acoustic field that supports the droplets.

6 DROPLET IGNITION STUDIES

Table I lists the techniques that were tried for igniting fuel droplets in this study. The first, and simplest, method was the use of a pre-ignited match. A series of attempts to ignite a levitated droplet resulted in a disruption of the acoustic field causing the droplet to fall out of suspension. The second technique used was a hot tungsten wire. Although repeated use of a glowing tungsten filament ended with eventual failure of the wire due to oxidation, the filament lasted long enough to observe the same results as those occurring with the lighted match.

The next technique employed a spark generator to pass a discharge through the suspended droplet. A spark gap 0.5 cm wide was created with two electrodes having diameters of approximately 0.05 cm. The electrodes were moved into a position where the gap

22

Top graph: Y-axis "(Volts)" from 0 to 0.4. X-axis "Frequency (Khz)" from 10 to 90. Legend: □ Supply, + Induced

Bottom graph: Y-axis "Diameter Squared (In^2)" from 0 to 0.0026. X-axis "Time (s)" from 0 to 400. Legend: □ iso—octane, + n—heptane, ◇ ethanol
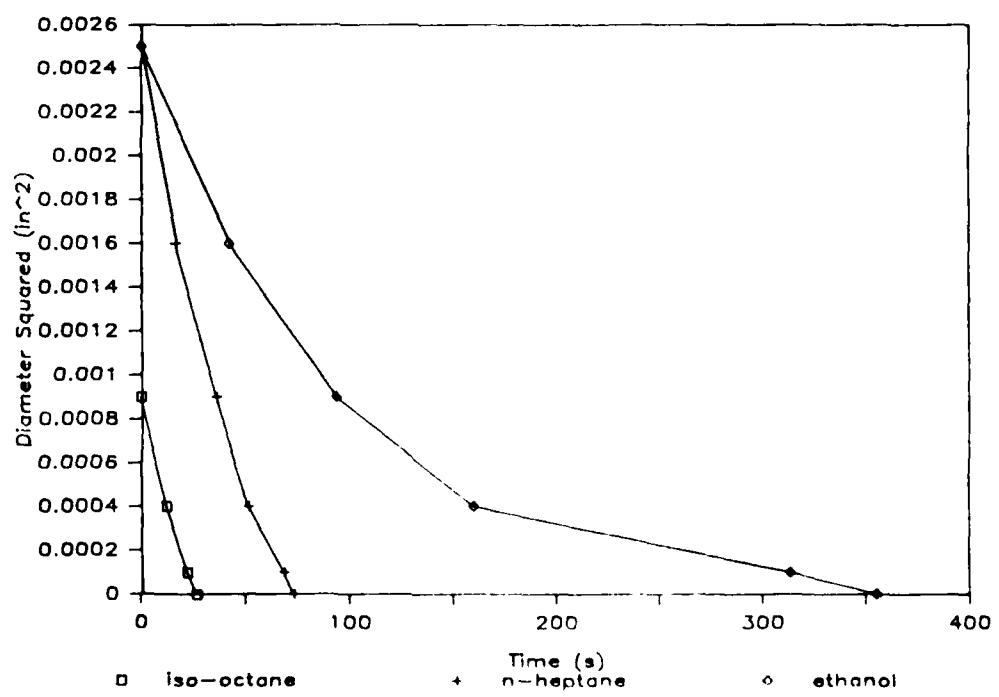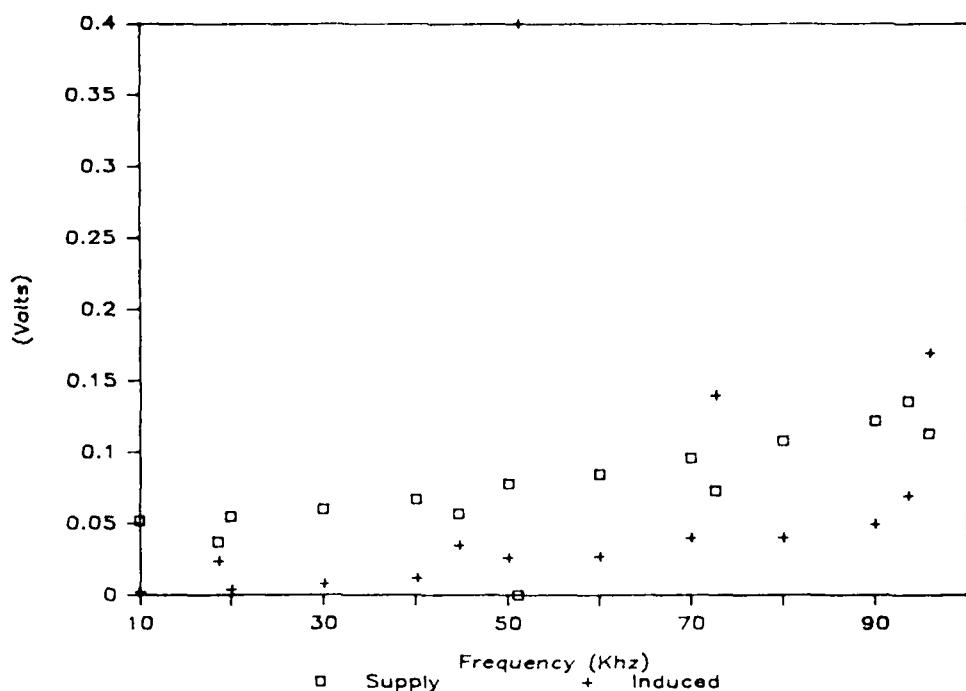
FIGURE 6

TABLE I

Ignition Techniques Studied

Technique	Fuel	Results
Open Flame	n-Hexane	Loss of Suspension
	iso-Octane	Loss of Suspension
		(all ignited on fiber)
Hot Wire (Chromel wire)	n-Hexane	Loss of Suspension
	Ethanol	Loss of Suspension
	Methanol	Loss of Suspension
Hot Wire (Tungsten)	n-Hexane	Ignition on Fiber Only
	Methanol	Ignition on Fiber Only
Spark Discharge	Decane	No Ignition
	n-Hexane	Ignition on Fiber Only
	Ethanol	No Ignition
	Methanol	No Ignition
Excimer Laser	Ethanol	No Ignition
	n-Hexane	No Ignition
CO_2 Laser	Ethanol	Loss of Suspension
	n-Hexane	Loss of Suspension
	Decane	Rapid Evaporation

contained the levitated droplet. A short duration, 25 kV spark
discharge was made to jump the gap. A large number of attempts
to ignite the droplets were made. Discharges appeared to pass
very close to, or even through the droplet with no apparent
effect other than to occasionally eject the droplet out of the
acoustic field. The reason for the failure of this technique is
speculative, but apparently the resonator sound energy inhibits
the ignition mechanisms associated with droplet combustion. This
problem does not occur with fiber suspended droplets which can be
ignited with a discharge.

A fourth technique employed an excimer laser (ArF) to induce
a breakdown of the air next to the droplet. The setup is shown
in Fig. 7. Sufficient energy was available to disintegrate the
droplet when it was in the beam path, or eject the droplet from
the acoustic field by shock wave disturbances. At lower energy
settings, a laser induced plasma could be observed at the beam
focus (a 10 cm focal length lens was used). Using both hexane
and ethanol droplets, the location of the plasma was moved to
positions above, below, and to the side of the droplet with no
apparent effect other than to set the droplet into oscillation.
The plasma was even caused to impinge slightly on the droplet
which caused violent oscillations or ejected the droplet from the
field. No ignition was observed.

The last technique t) 'ed was ignition using a CO_2 laser
emitting at 10.6 micrometers. The total available power for this
experiment was 50 watts, however, much reduced power levels were
necessary in order to conduct the experiment. Unfocussed
radiation from the laser was used to fully illuminate the droplet
from one side. From wavelength considerations, it was
anticipated that rapid heating would be available for the
experiment. Droplets attached to capillary tubes were first
studied. Rapid evaporation could be induced in the attached
droplets with some evidence of pyrolysis occurring from smoke .
generated during the process. No ignition was observed in these

ArF EXCIMER LASER

LASER CONTROL

APERTURE

LENS

RESONATOR

REFLECTOR

LAB JACK

FIGURE 7

26
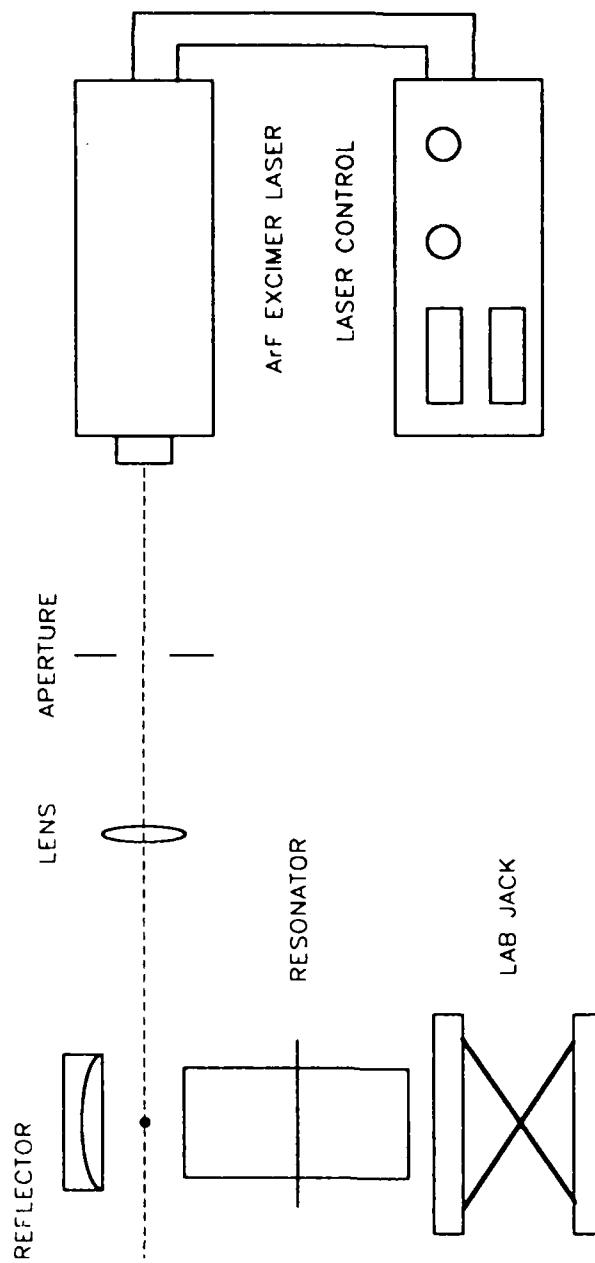
preliminary experiments. During droplet levitation, decane remained stable during irradiation. Rapid evaporation was observed with the CO_2 laser output at approximately 2 to 3 watts. Again, some evidence of pyrolysis was observed in the form of smoke. Other liquids such as hexane and ethanol became unstable upon irradiation and fell out of suspension. No ignition was observed during these experiments. Focussing the laser beam was not attempted, neither was use made of CO_2 laser breakdown as a potential ignition source. It was believed that such attempts would not be productive because of the violent nature accompanying plasma formation at a wavelength of 10.6 micrometers.

The final results of the ignition experiments were negative. Although many techniques were explored for their usefulness, no minimum perturbation ignition method was found in this study.

7 CONCLUSION

Piezoelectrically driven ultrasonic resonators were found to be simple in design, construction, and testing. Over a dozen resonator configurations were made and tested for their operating characteristics. Two proved to be especially reliable at levitating droplets and were subsequently employed in vaporization and ignition studies on liquid fuels such as ethanol, n-heptane, iso-octane, and decane. These tests were performed at resonant frequencies of approximately 20 kHz and 50 kHz, the former value being a fundamental resonator frequency and the latter value being a first harmonic. Droplet stability in suspension was not as good as desired for accurate determinations of droplet diameters. However, the stability was more than adequate to test various ignition techniques which included use of a) hot wires, b) spark discharges, c) open flames, d) excimer laser produced air breakdown, and e) CO_2 laser heating. All attempts proved unsuccessful. The reason for this is not known at this time but the effect of the acoustic pressure field on ignition is a key area of concern. Vaporization tests conducted

on the droplets demonstrated that the suspending force in the acoustic field is equivalent to approximately a 12 cm/s flow across the droplet. The magnitude of this velocity, although small, could have detrimental effects on the droplet ignition mechanisms.

REFERENCES

1) W.A. Oran and L.H. Berge, Rev. Sci. Instrum., 53, 851 (1982).

2) A.R. Hanson, E.G. Domich, H.S. Adams, Rev. Sci.Instrum., 35, 1031 (1964).

3) E.J. Davis, Aerosol Science and Technology, 2, 121 (1983).

4) R.R. Perron, IEEE Trans. Sonics and Ultrasonics, SU-14, 149 (1967).

5) H. Minchenko, IEEE Trans. Sonics and Ultrasonics, SU-16, 126 (1969).

6) R.R. Wymark, Ultrasonics, 13, 251 (1975).

7) M.C. Lee and I. Feng, Rev. Sci. Instrum., 53, 854 (1982).

8) E.H. Trinh, Rev. Sci. Instrum., 56, 2059 (1985).

9) A.M. Kanury, "Combustion Phenomena," (Gordon and Breach Science Publishers, New York, 1975), p. 166.

APPENDIX A

VAPORIZATION DATA

1 1/2" RESONATOR tightened to 80 ft-lb
35 volts driving at 20.7 kHz
160 mV acoustic pickup
76.6 F

n-heptane

TIME [s]	DIA [in]	TIME [s]	DIA [in]
0	0.05	-20	0.07
15	0.04	-5	0.06
35	0.03	0	0.05
55	0.015	10	0.04
67	0.01	40	0.025
70	0.000	50	0.02
		65	0.01
		70	0.000

TIME [s]	DIA [in]	TIME [s]	DIA [in]
-40	0.08	-30	0.08
-23	0.07	-20	0.07
-14	0.06	-10	0.06
0	0.05	0	0.05
10	0.04	31	0.04
21	0.035	49	0.03
47	0.02	69	0.02
60	0.015	80	0.01
67	0.01	88	0.000

		AVERAGE VALUES	
TIME [s]	DIA [in]	TIME [s]	DIA [in]
-15	0.06	0	0.05
0	0.05	16.8	0.04
18	0.04	36.4	0.03
36	0.03	51.9	0.02
45	0.02	68.8	0.01
65	0.01	73.3	0.000
67	0.000		

ethanol

TIME [s]	DIA [in]		TIME [s]	DIA [in]
-40	0.06		0	0.03
0	0.05		45	0.04
40	0.04		130	0.025
86	0.03		209	0.02
152	0.02		318	0.01
350	0.01		345	0.000
406	0.000			

AVERAGE VALUES

TIME [s]	DIA [in]
0	0.05
42.5	0.04
94.0	0.03
180.5	0.02
334.0	0.01
375.5	0.000

iso-octane

TIME [s]	DIA [in]	TIME [s]	DIA [in]
-8	0.04	0	0.03
0	0.03	11	0.02
15	0.02	19	0.015
21	0.01	24	0.01
27	0.000		

TIME [s]	DIA [in]	TIME [s]	DIA [in]
-9	0.04	0	0.03
0	0.03	14	0.02
10	0.02	24	0.01
16	0.015	28	0.000
20	0.01		
23	0.000		

AVERAGE VALUES

TIME [s]	DIA [in]
0	0.03
12.5	0.02
22.3	0.01
26.6	0.000

methanol

TIME [s]	DIA [in]
0	0.04
245	0.000

To unstable to make any further measurements

35

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
12	Administrator Defense Technical Info Center ATTN: DTIC-FDAC Cameron Station, Bldg. 5 Alexandria, VA 22304-6145	1	Director US Army Aviation Research and Technology Activity Ames Research Center Moffett Field, CA 94035-1099
1	HQ DA DAMA-ART-M Washington, DC 20310	4	Commander US Army Research Office ATTN: R. Ghirardelli D. Mann R. Singleton R. Shaw P.O. Box 12211 Research Triangle Park, NC 27709-2211
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001		
10	C.I.A. OIR/DB/Standard GE47 HQ Washington, DC 20505	1	Commander US Army Communications - Electronics Command ATTN: AMSEL-ED Fort Monmouth, NJ 07703
1	Commander US Army ARDEC ATTN: SMCAR-MSI Dover, NJ 07801-5001	1	Commander CECOM R&D Technical Library ATTN: AMSEL-IM-L, Reports Section B.2700 Fort Monmouth, NJ 07703-5000
1	Commander US Army ARDEC ATTN: SMCAR-TDC Dover, NJ 07801	2	Commander Armament R&D Center US Army AMCCOM ATTN: SMCAR-LCA-G, D.S. Downs J.A. Lannon Dover, NJ 07801
1	Commander US AMCCOM ARDEC CCAC Benet Weapons Laboratory ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050		
1	US Army Armament, Munitions and Chemical Command ATTN: AMSMC-IMP-L Rock Island, IL 61299-7300	1	Commander Armament R&D Center US Army AMCCOM ATTN: SMCAR-LC-G, L. Harris Dover, NJ 07801
1	Commander US Army Aviation Systems Command ATTN: AMSAV-ES 4300 Goodfellow Blvd. St. Louis, MO 63120-1798	1	Commander Armament R&D Center US Army AMCCOM ATTN: SMCAR-SCA-T, L. Stiefel Dover, NJ 07801

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
1	Commander US Army Missile Command Research, Development and Engineering Center ATTN: AMSMI-RD Redstone Arsenal, AL 35898	1	Office of Naval Research Department of the Navy ATTN: R.S. Miller, Code 432 800 N. Quincy Street Arlington, VA 22217

1	Commander
	US Army Missile and Space
	  Intelligence Center
	ATTN: AMSMI-YDL
	Redstone Arsenal, AL 35898-5000
		1	Commander
			Naval Air Systems Command
			ATTN: J. Ramnarace,
			      AIR-54111C
			Washington, DC 20360

2	Commander
	US Army Missile Command
	ATTN: AMSMI-RK, D.J. Ifshin
	              W. Wharton
	Redstone Arsenal, AL 35898
		2	Commander
			Naval Ordnance Station
			ATTN: C. Irish
			      P.L. Stang, Code 515
			Indian Head, MD 20640

1	Commander US Army Missile Command ATTN: AMSMI-RKA, A.R. Maykut Redstone Arsenal, AL 35898-5249	1	Commander Naval Surface Weapons Center ATTN: J.L. East, Jr., G-23 Dahlgren, VA 22448-5000

1	Commander
	US Army Tank Automotive
	  Command
	ATTN: AMSTA-TSL
	Warren, MI 48397-5000
		2	Commander
			Naval Surface Weapons Center
			ATTN: R. Bernecker, R-13
			      G.B. Wilmot, R-16
			Silver Spring, MD 20902-5000

1	Director US Army TRADOC Systems Analysis Center ATTN: ATOR-TSL White Sands Missile Range, NM 88002-5502	1	Commander Naval Weapons Center ATTN: R.L. Derr, Code 389 China Lake, CA 93555
1	Commandant US Army Infantry School ATTN: ATSH-CD-CS-OR Fort Benning, GA 31905-5400	2	Commander Naval Weapons Center ATTN: Code 3891, T. Boggs K.J. Graham China Lake, CA 93555

1	Commander
	US Army Development and
	  Employment Agency
	ATTN: MODE-ORO
	Fort Lewis, WA 98433-5000
		5	Commander
			Naval Research Laboratory
			ATTN: M.C. Lin
			      J. McDonald
			      E. Oran
			      J. Shnur
			      R.J. Doyle, Code 6110
			Washington, DC 20375

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
1	Commanding Officer Naval Underwater Systems Center Weapons Dept. ATTN: R.S. Lazar/Code 36301 Newport, RI 02840	1	OSD/SDIO/UST ATTN: L.H. Caveny Pentagon Washington, DC 20301-7100
1	Superintendent Naval Postgraduate School Dept. of Aeronautics ATTN: D.W. Netzer Monterey, CA 93940	1	Aerojet Solid Propulsion Co. ATTN: P. Micheli Sacramento, CA 95813

4	AFRPL/DY, Stop 24
	ATTN: R. Corley
	       R. Geisler
	       J. Levine
	       D. Weaver
	Edwards AFB, CA 93523-5000
		1	Applied Combustion
			  Technology, Inc.
			ATTN: A.M. Varney
			P.O. Box 17885
			Orlando, FL 32860

1	AFRPL/MKPB, Stop 24
	ATTN: B. Goshgarian
	Edwards AFB, CA 93523-5000
		2	Applied Mechanics Reviews
			The American Society of
			  Mechanical Engineers
			ATTN: R.E. White
			      A.B. Wenzel
			345 E. 47th Street
			New York, NY 10017

1	AFOSR ATTN: J.M. Tishkoff Bolling Air Force Base Washington, DC 20332	1	Atlantic Research Corp. ATTN: M.K. King 5390 Cherokee Avenue Alexandria, VA 22314
1	AFATL/DOIL (Tech Info Center) Eglin AFB, FL 32542-5438	1	Atlantic Research Corp. ATTN: R.H.W. Waesche 7511 Wellington Road Gainesville, VA 22065
1	Air Force Weapons Laboratory AFWL/SUL ATTN: V. King Kirtland AFB, NM 87117	1	AVCO Everett Rsch. Lab. Div. ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149
1	NASA Langley Research Center Langley Station ATTN: G.B. Northam/MS 168 Hampton, VA 23365	1	Battelle Memorial Institute Tactical Technology Center ATTN: J. Huggins 505 King Avenue Columbus, OH 43201

4	National Bureau of Standards
	ATTN: J. Hastie
	      M. Jacox
	      T. Kashiwagi
	      H. Semerjian
	US Department of Commerce
	Washington, DC 20234
		1	Cohen Professional Services
			ATTN: N.S. Cohen
			141 Channing Street
			Redlands, CA 92373

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
1	Exxon Research & Eng. Co. Government Research Lab ATTN: A. Dean P.O. Box 48 Linden, NJ 07036	1	Hercules, Inc. Bacchus Works ATTN: K.P. McCarty P.O. Box 98 Magna, UT 84044
1	Ford Aerospace and Communications Corp. DIVAD Division Div. Hq., Irvine ATTN: D. Williams Main Street & Ford Road Newport Beach, CA 92663	1	Honeywell, Inc. Government and Aerospace Products ATTN: D.E. Broden/ MS MN50-2000 600 2nd Street NE Hopkins, MN 55343
1	General Applied Science Laboratories, Inc. ATTN: J.I. Erdos 425 Merrick Avenue Westbury, NY 11590	1	IBM Corporation ATTN: A.C. Tam Research Division 5600 Cottle Road San Jose, CA 95193
1	General Electric Armament & Electrical Systems ATTN: M.J. Bulman Lakeside Avenue Burlington, VT 05401	1	IIT Research Institute ATTN: R.F. Remaly 10 West 35th Street Chicago, IL 60616
1	General Electric Company 2352 Jade Lane Schenectady, NY 12309	2	Director Lawrence Livermore National Laboratory ATTN: C. Westbrook M. Costantino
1	General Electric Ordnance Systems ATTN: J. Mandzy 100 Plastics Avenue Pittsfield, MA 01203	1	P.O. Box 808 Livermore, CA 94550 Lockheed Missiles & Space Co. ATTN: George Lo 3251 Hanover Street Dept. 52-35/B204/2 Palo Alto, CA 94304
2	General Motors Rsch Labs Physics Department ATTN: T. Sloan R. Teets Warren, MI 48090	1	Los Alamos National Lab ATTN: B. Nichols T7, MS-B284 P.O. Box 1663 Los Alamos, NM 87545
2	Hercules, Inc. Allegany Ballistics Lab. ATTN: R.R. Miller E.A. Yount P.O. Box 210 Cumberland, MD 21501	1	National Science Foundation ATTN: A.B. Harvey Washington, DC 20550

40

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
1	Olin Corporation Smokeless Powder Operations ATTN: V. McDonald P.O. Box 222 St. Marks, FL 32355	3	SRI International ATTN: G. Smith D. Crosley D. Golden 333 Ravenswood Avenue Menlo Park, CA 94025
1	Paul Gough Associates, Inc. ATTN: P.S. Gough 1048 South Street Portsmouth, NH 03801	1	Stevens Institute of Tech. Davidson Laboratory ATTN: R. McAlevy, III Hoboken, NJ 07030
2	Princeton Combustion Research Laboratories, Inc. ATTN: M. Summerfield N.A. Messina 475 US Highway One Monmouth Junction, NJ 08852	1	Textron, Inc. Bell Aerospace Co. Division ATTN: T.M. Ferger P.O. Box 1 Buffalo, NY 14240
1	Hughes Aircraft Company ATTN: T.E. Ward 8433 Fallbrook Avenue Canoga Park, CA 91303	1	Thiokol Corporation Elkton Division ATTN: W.N. Brundige P.O. Box 241 Elkton, MD 21921
1	Rockwell International Corp. Rocketdyne Division ATTN: J.E. Flanagan/HB02 6633 Canoga Avenue Canoga Park, CA 91304	1	Thiokol Corporation Huntsville Division ATTN: R. Glick Huntsville, AL 35807
4	Sandia National Laboratories Combustion Sciences Dept. ATTN: R. Cattolica S. Johnston P. Mattern D. Stephenson Livermore, CA 94550	3	Thiokol Corporation Wasatch Division ATTN: S.J. Bennett P.O. Box 524 Brigham City, UT 84302
1	Science Applications, Inc. ATTN: R.B. Edelman 23146 Cumorah Crest Woodland Hills, CA 91364	1	TRW ATTN: M.S. Chou MSR1-1016 1 Parke Redondo Beach, CA 90278
1	Science Applications, Inc. ATTN: H.S. Pergament 1100 State Road, Bldg. N Princeton, NJ 08540	1	United Technologies ATTN: A.C. Eckbreth East Hartford, CT 06108

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
3	United Technologies Corp. Chemical Systems Division ATTN: R.S. Brown T.D. Myers (2 copies) P.O. Box 50015 San Jose, CA 95150-0015	1	University of California Los Alamos Scientific Lab. P.O. Box 1663, Mail Stop B216 Los Alamos, NM 87545

2	United Technologies Corp.
	ATTN: R.S. Brown
	      R.O. McLaren
	P.O. Box 358
	Sunnyvale, CA 94086
		2	University of California,
			  Santa Barbara
			Quantum Institute
			ATTN: K. Schofield
			      M. Steinberg
			Santa Barbara, CA 93106

1	Universal Propulsion Company
	ATTN: H.J. McSpadden
	Black Canyon Stage 1
	Box 1140
	Phoenix, AZ 85029
		2	University of Southern
			  California
			Dept. of Chemistry
			ATTN: S. Benson
			      C. Wittig
			Los Angeles, CA 90007

1	Veritay Technology, Inc. ATTN: E.B. Fisher 4845 Millersport Highway P.O. Box 305 East Amherst, NY 14051-0305	1	Case Western Reserve Univ. Div. of Aerospace Sciences ATTN: J. Tien Cleveland, OH 44135
1	Brigham Young University Dept. of Chemical Engineering ATTN: M.W. Beckstead Provo, UT 84601	1	Cornell University Department of Chemistry ATTN: T.A. Cool Baker Laboratory Ithaca, NY 14853
1	California Institute of Tech. Jet Propulsion Laboratory ATTN: MS 125/159 4800 Oak Grove Drive Pasadena, CA 91103	1	Univ. of Dayton Rsch Inst. ATTN: D. Campbell AFRPL/PAP Stop 24 Edwards AFB, CA 93523

1	California Institute of
	  Technology
	ATTN: F.E.C. Culick/
	      MC 301-46
	204 Karman Lab.
	Pasadena, CA 91125
		1	University of Florida
			Dept. of Chemistry
			ATTN: J. Winefordner
			Gainesville, FL 32611

1	University of California,
	  Berkeley
	Mechanical Engineering Dept.
	ATTN: J. Daily
	Berkeley, CA 94720
		3	Georgia Institute of
			  Technology
			School of Aerospace
			  Engineering
			ATTN: E. Price
			      W.C. Strahle
			      B.T. Zinn
			Atlanta, GA 30332

DISTRIBUTION LIST

No. Of Copies	Organization	No. Of Copies	Organization
1	University of Illinois Dept. of Mech. Eng. ATTN: H. Krier 144MEB, 1206 W. Green St. Urbana, IL 61801	1	Purdue University School of Aeronautics and Astronautics ATTN: J.R. Osborn Grissom Hall West Lafayette, IN 47906
1	Johns Hopkins University/APL Chemical Propulsion Information Agency ATTN: T.W. Christian Johns Hopkins Road Laurel, MD 20707	1	Purdue University Department of Chemistry ATTN: E. Grant West Lafayette, IN 47906
1	University of Michigan Gas Dynamics Lab Aerospace Engineering Bldg. ATTN: G.M. Faeth Ann Arbor, MI 48109-2140	2	Purdue University School of Mechanical Engineering ATTN: N.M. Laurendeau S.N.B. Murthy TSPC Chaffee Hall West Lafayette, IN 47906
1	University of Minnesota Dept. of Mechanical Engineering ATTN: E. Fletcher Minneapolis, MN 55455	1	Rensselaer Polytechnic Inst. Dept. of Chemical Engineering ATTN: A. Fontijn Troy, NY 12181
3	Pennsylvania State University Applied Research Laboratory ATTN: K.K. Kuo H. Palmer M. Micci University Park, PA 16802	1	Stanford University Dept. of Mechanical Engineering ATTN: R. Hanson Stanford, CA 94305
1	Polytechnic Institute of NY Graduate Center ATTN: S. Lederman Route 110 Farmingdale, NY 11735	1	University of Texas Dept. of Chemistry ATTN: W. Gardiner Austin, TX 78712
2	Princeton University Forrestal Campus Library ATTN: K. Brezinsky I. Glassman P.O. Box 710 Princeton, NJ 08540	1	University of Utah Dept. of Chemical Engineering ATTN: G. Flandro Salt Lake City, UT 84112
1	Princeton University MAE Dept. ATTN: F.A. Williams Princeton, NJ 08544	1	Virginia Polytechnic Institute and State University ATTN: J.A. Schetz Blacksburg, VA 24061

DISTRIBUTION LIST

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the
reports it publishes. Your comments/answers to the items/questions below will
aid us in our efforts.

1. BRL Report Number_____Date of Report_____

2. Date Report Received_____

3. Does this report satisfy a need? (Comment on purpose, related project, or
other area of interest for which the report will be used.)_____

_____

_____

4. How specifically, is the report being used? (Information source, design
data, procedure, source of ideas, etc.)_____

_____

_____

5. Has the information in this report led to any quantitative savings as far
as man-hours or dollars saved, operating costs avoided or efficiencies achieved,
etc? If so, please elaborate._____

_____

_____

6. General Comments. What do you think should be changed to improve future
reports? (Indicate changes to organization, technical content, format, etc.)

_____

_____

_____

	Name_____
CURRENT ADDRESS	Organization_____
	Address_____
	City, State, Zip

7. If indicating a Change of Address or Address Correction, please provide the
New or Correct Address in Block 6 above and the Old or Incorrect address below.

	Name_____
OLD ADDRESS	Organization_____
	Address_____
	City, State, Zip

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ FOLD HERE ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐

Director
US Army Ballistic Research Laboratory
ATTN: DRXBR-OD-ST
Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE. $300

| **BUSINESS REPLY MAIL** |
| FIRST CLASS   PERMIT NO 12062   WASHINGTON, DC |

POSTAGE WILL BE PAID BY DEPARTMENT OF THE ARMY

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

Director
US Army Ballistic Research Laboratory
ATTN: DRXBR-OD-ST
Aberdeen Proving Ground, MD 21005-9989
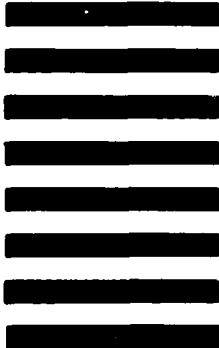
‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ FOLD HERE ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐ ‐

END

DATE
FILMED

8-88

DTIC